Simulation of a power electronic conversion system with short-term energy storage for actively controlled wave energy converters

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***Abstract*—A simulation study is conducted to assess the feasibility of a Wave Energy Converter Power Electronic Converter architecture to achieve a four quadrant torque demand resulting from an active control strategy. The system consists of four induction generators controlled by three phase inverters, a DC bus with short term energy storage provided by supercapacitors and batteries, and an active rectifier to control the DC bus voltage and provide AC power to the grid. The components are realistically modelled and it is shown that the torque and speed requirements of the active control strategy can be achieved and that the electrical energy storage can provide required reactive power on a wave-by-wave time scale and longer term energy supply during a lull in wave excitation. The WaveSub WEC is used as a target device in order to make a meaningful study with realistic inputs. However the architecture of the PEC system is applicable to any device with a bi-directional rotary PTO requiring four-quadrant active control at the generators. Furthermore the PEC architecture and simulation model are readily expandable to arrays of wave energy converters.**

***Index Terms*—Wave Energy Converter, Power Take-Off, Active Control, Power Electronic Conversion**

I. Introduction

The purpose of a ocean wave energy converter (WEC) is to convert the low speed, high force reciprocating wave input into grid compatible electrical power. All WECs have a power take-off system (PTO) as the interface between the prime mover (for example a float or paddle) and the electrical grid. Some WECs may use a hydraulic PTO which enables the de-coupling of the prime-mover and generation sides of the machine through rectification and accumulation to create a unidrectional smoothed power flow. However this does not allow for the use of four-quadrant active control schemes such as Model Predictive Control [1] or Simple and Effective control [2], which have been shown to potentially enable significant increases in overall power capture. Many WEC designs have a direct transmission (e.g. linear electric generators [3] or rotary mechanical gearbox and electrical generators [4].

Unlike for a wind turbine, the input to a WEC PTO is bi-directional and highly variable in intensity. Many architectures have been proposed in order to convert power efficiently in such a situation. In [5] three potential architectures are simulated, comprising of induction generators (IG) with either a static synchronous compensator (STATCOM) or full converter to manage reactive power, and doubly fed induction generators (DFIG) with a rotor converter. The ability to implement a two quadrant latching control strategy [6] and provide power smoothing using battery and supercapacitor storage is shown. In [7] a practical control and power management strategy for a DFIG PEC system is simulated in conjunction with a model of a paddle type WEC. In [8] a system of several permanent magnet synchronous generators (PMSG) connected to a common DC bus with electrical energy storage is considered. This is applied to a simulated farm of Fred Olsen Lifesafer WECs. It is shown that grid compatible power can be generated and that the array of devices can provide power smoothing with appropriate spatial arrangement. A similar architecture is described in [9] for the ISWEC device, using PMSGs on a common DC bus with ultracapacitors and batteries to provide short-term energy storage. An experimental study for a WEC equipped with a linear electric generator, a grid-connected voltage source converter (VSC) and LCL filtering to attenuate switching ripples is described in [10]. Improved power quality in terms of reduction of higher order harmonics is demonstrated.

Here we use a system comprising of induction generators under direct torque control to provide the necessary control inputs to the prime mover. Four IGs are connected in parallel to a common DC bus and an active rectifier is used to control the Bus voltage and transfer AC power to the grid side. Short term energy storage is provided from a combined battery and supercapacitor bank connected to the DC bus. This is designed to provide the reactive power requirement for the active control strategy on a wave-to-wave time scale and to provide a base power generation for periods of lulls in the wave conditions (periods of 10s of seconds). The WaveSub WEC is used as a target device in order to make a meaningful study with realistic inputs. However the architecture of the PEC system is applicable to any device with a bi-directional rotary PTO requiring four-quadrant active control at the generator. A previous study [11] has developed an active control strategy for WaveSub which can potentially increase power capture by greater than 50% in a wide range of operating sea conditions. The torque and speed data from that study is used here to provide inputs to the PEC simulation. This paper presents a feasible PEC architecture with the primary focus of providing the necessary control actions and transferring power to the grid. The secondary aim is the removal of the need for power transfer from the grid to the WEC PTO during motoring periods in the four-quadrant control. This is achieved through provision of the power required by the PTO from a short-term electrical energy storage system. This could reduce the cost of the PEC system and increase efficiency and reliability.

The paper is organised as follows. Section II describes the WaveSub WEC. Section III describes the active control strategy applied. Section IV describes the modelling of the PTO generation, PEC and storage systems. Simulation results for typical operating conditions and lulls in wave excitation are presented and discussed in section V. Finally, conclusions are provided in section VI.

II. The WaveSub WEC

WaveSub is a submerged point absorber WEC under development by Marine Power Systems Ltd. Figure 1 shows an illustration of a full scale concept device.

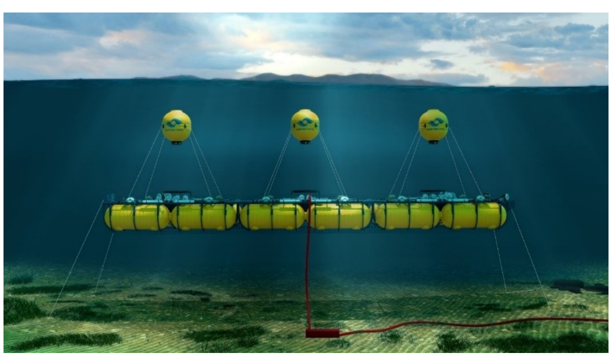

Fig. 1. Illustration of full scale multi-float WaveSub concept [Image provided by Marine Power Systems Ltd.]

This study uses a single section of this device, comprising a single float with four taut tethers wrapped around individual drums connected to gearboxes and rotary generators. A block diagram representation of the complete system is shown in Figure 2.

The wave excitation force causes the floats to move in an orbital path which causes the tethers to extend and retract. This

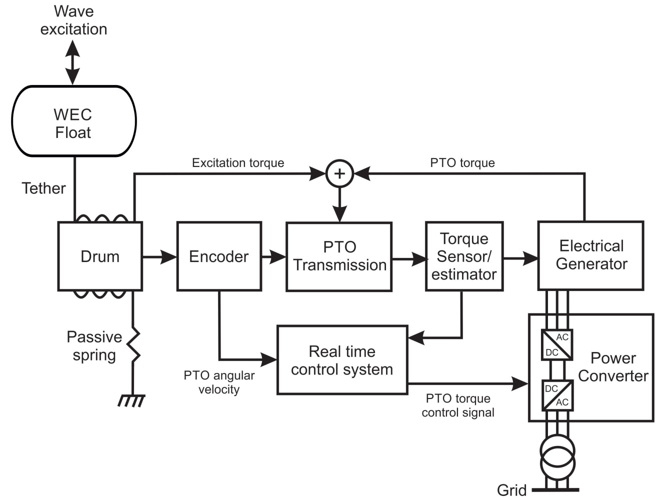

Fig. 2. Block diagram representation of WEC/PTO systems

results in rotation of the drums and subsequently rotation of the generators following a step up in speed resulting from gearboxes. Stiffness is provided by passive springs attached to each tether or drum and these are tuned to bring the resonant frequency of the float into the range of most commonly occurring wave excitation frequencies. An active control strategy adjusts the torque at the generators in order to maximise power capture by the float. The generator torque and power flow to the grid are controlled by the PEC system which is the main focus of this paper.

III. Prime Mover Active Control Strategy

The multiple degree of freedom active control strategy previously developed in [11] is based on the Simple and Effective strategy proposed in [2]. A velocity reference trajectory for the float is evolved based upon the estimated wave excitation force and knowledge of the WEC/PTO dynamics and physical position constraints. The overall control strategy is illustrated in Figure 3.

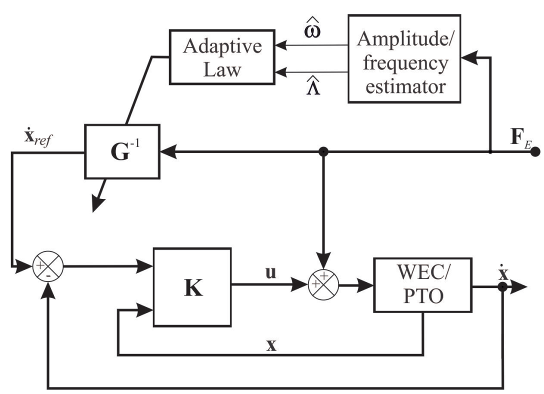

Fig. 3. Illustration of Simple and Effective control strategy with LQR velocity tracking (adapted from [2])

Here $\mathbf{F}_E(t) \in R^{6\times1}$ is the wave excitation force, $\mathbf{u} \in R^{6\times1}$ is the vector of control forces (transformable to four control torque commands for the generators via the kinematic Jacobian matrix for the system [11]) and $\mathbf{x} \in R^{6\times1}$ is the state vector given by

$$\mathbf{x} = [x\ y\ z\ \theta_x\ \theta_y\ \theta_z]^T \tag{1}$$

The vector of Cartesian velocity reference signals is given by

$$\dot{\mathbf{x}}_{ref}(t) = \mathbf{G}^{-1}(t)\mathbf{F}_E(t) \tag{2}$$

where $\mathbf{G}^{-1}(t) \in R^{6\times6}$ is a time-varying gain adapted to provide the optimal trajectory for power absorption when position constraints are not violated. Based upon estimates of the instantaneous amplitude $\hat{\Lambda}(t)$ and frequency $\hat{\omega}(t)$ of the excitation force and knowledge of the plant dynamics, $\mathbf{G}^{-1}(t)$ is limited to maintain motion within constraints.

Tracking of the velocity reference is achieved using a Linear Quadratic Regulator (LQR) state feedback controller under the assumption all states may be measured or accurately estimated. This leads to appropriate design of the feedback gain matrix $\mathbf{K}$ to balance tracking performance against control effort. If good tracking of the float velocity reference is achieved then the power absorbed by the WEC will be near optimal.

In [11] the active control system performance was compared against a benchmark optimal passive system. Figure 4 shows the instantaneous mechanical power captured by the PTO for the optimally tuned passive system and the active control system for a typical irregular sea-state. Clearly an increase in mean captured power is seen, as is the requirement for bi-directional power flow in the PTO. The PTO torque and velocity corresponding to this data form the basis of the simulation results presented in this paper. For details of the system dynamics and control strategy the interested reader is directed to [11].

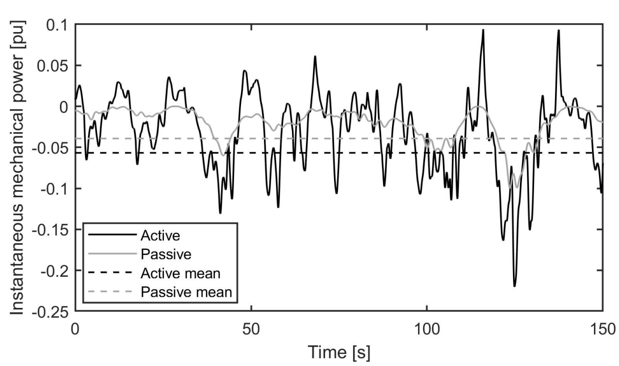

Fig. 4. Instantaneous power under controlled conditions (sea state $H_s = 3m$, $T_e = 10s$) for full WEC-Sim model

IV. Power Take Off System Modelling

As illustrated in Figure 2, the PTO system consists of two transmission stages. All systems are modelled in the MATLAB SIMLINK/SIMSCAPE environment with a particular focus on accurately capturing the dynamic operation of the generators and PEC systems.

A. Mechanical Transmission

Four taut cables turn drums to convert linear motion into rotation. Each drum is connected to a gearbox to step up the rotational speed of the generators. This transmission is not explicitly modelled so it is represented as an ideal mechanical gearbox with a ratio of 40:1. Alternatively a hydraulic transmission could be used. This would enable higher gear ratios if required and would also allow for the possibility of rectification for unidirectional rotation of the generator. A model of such a transmission can be readily incorporated. The generators are modelled as asynchronous induction machines with squirrel-cage rotors and two pole pairs. This type of generator was selected due to the low maintenance requirement, which is a key design attribute for WECs. The generators are controlled in four quadrants to achieve a demand torque set by the active control system. The speed of the generators is imposed as an external load taken from data generated in the study described in [11]. Therefore the mechanical inertia of the generators is not modelled and must be incorporated with the WEC system dynamic model. The rated power of the generators is selected based upon the results from active control studies using 144 representative irregular sea states [11]. The parameters are not provided here and power outputs are presented in [p.u] in order to anonymise the data.

B. Power Electronic Conversion

Figure 5 shows the general arrangement for multiple generators.

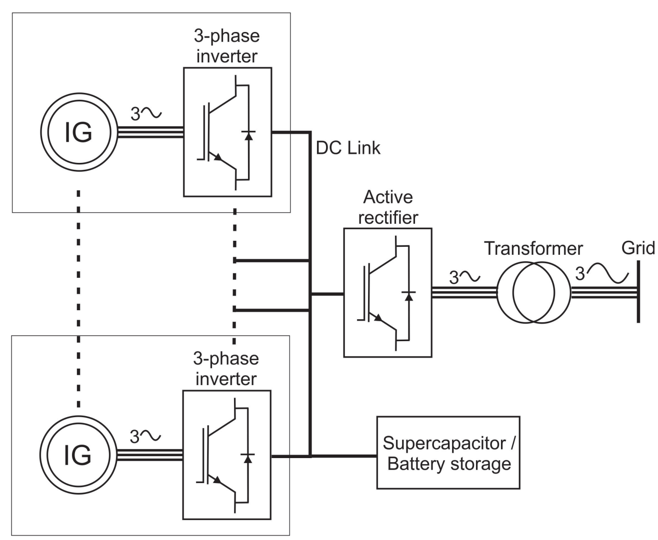

Fig. 5. Overview of power electronic conversion system for multiple generators.

Four induction generators are controlled by three-phase inverters which are connected to a common DC bus. Short term electrical energy storage is supplied to the DC bus by a combined supercapacitor-battery system. An active rectifier converts the DC power to three-phase AC which is transformed to grid voltage. The grid is modelled as an ideal 25kV voltage source with a frequency of 60Hz. A transformer is placed between the grid and active rectifier. The AC-DC-AC conversion decouples the grid from the generators and enables efficient power conversion from the bi-directional and highly irregular wave power source.

Figure 6 shows the arrangement of the PEC systems for a single induction generator. The operation of the different systems is described in the following subsections. The aim is to provide a systems level overview rather than provide full details of the machine level control operations. Details of these aspects may be found in many textbooks on power electronics, for example [12].

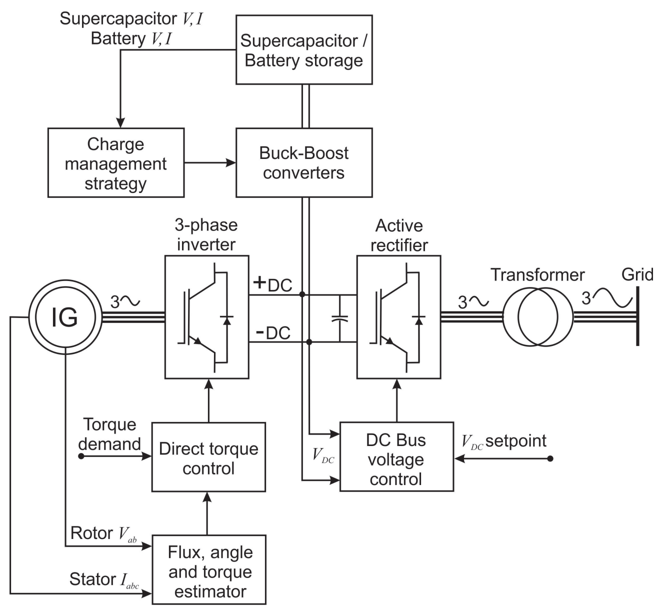

Fig. 6. Schematic of power electronic conversion system for a single generator.

1) Four quadrant inverters: A detailed model of a three-leg, two-level inverter is used. The bridge is comprised of forced commutated insulated-gate bipolar transistors (IGBT) which are switched according to a direct torque control (DTC) logic using space vector modulation of a PWM signal. This aims to directly control the torque and stator flux of the induction generator. The torque and flux are estimated from the induction generator voltages and currents and are regulated by proportional-integral (PI) compensators.

2) Active rectifier: The active rectifier is modelled as a three-phase IGBT device switched by a PWM signal modulated by a PI compensator to regulate the DC bus voltage and AC line currents. The DC bus voltage is set at 750V. The common DC bus enables direct power sharing between the four generators so generating units can directly power motoring units. This smooths power flow to the grid and multiple units in an array can be connected in the same way to further smooth the total power generation. This could potentially eliminate the need for short-term energy storage.

3) Short term electrical energy storage: With reference to Figure 4, it can be seen that there is a requirement for bi-directional power flow in the PTO. While this can be achieved with the proposed PEC architecture, it may not be desirable or possible in many cases. Short term energy storage in supercapacitors is used here to provide the power required during motoring phases of the generators on a wave-by-wave time scale. Supercapacitors can provide rapid injections of power to achieve this and can be sized based upon estimations of the energy required in the largest common sea states. It may also be required for the WEC to remain connected to the grid and generating power during lulls in the wave excitation. In this case a larger energy store would be required and could be provided by batteries. The batteries must be sized for the required power generation and a maximum anticipated lull time. The response time of the battery is much slower than that of the supercapacitors and this is modelled as a rate limit on charge/discharge currents. A power management strategy is implemented to balance the power supplied/absorbed by the supercapacitors and batteries in order to provide the necessary power and maintain the state of charge (SOC). The charge/discharge of the storage system is controlled by standard buck-boost converters.

V. Simulation Results

A. Power Conversion in normal operation

Results using a Pierson-Moskowitz (PM) spectrum with significant wave height $H_s = 3\text{m}$ and energy period $T_e = 10\text{s}$ (see Figure 7) are presented in detail, giving insight into the internal signals and processes occurring within the PEC system. This sea state represents a typical sea state for which the device is sized. The required control torque and speed at each generator was calculated from the data obtained for this sea state in [11] and these were used as the simulation inputs, with torque being a demand and speed being an imposed load.

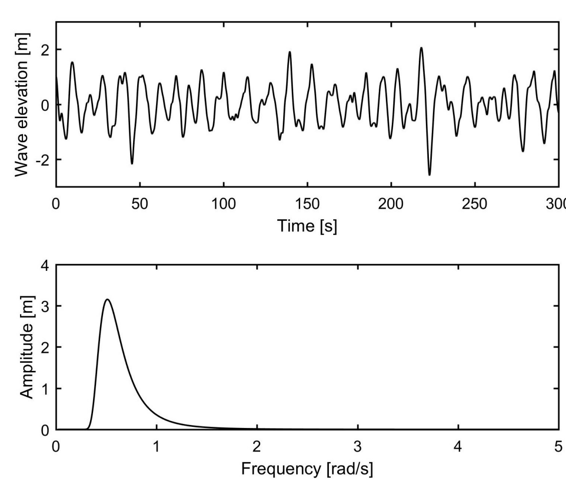

Fig. 7. Wave elevation and spectrum for irregular waves (Pierson-Moskowitz with $H_s = 3\text{m}$ $T_e = 10\text{s}$)

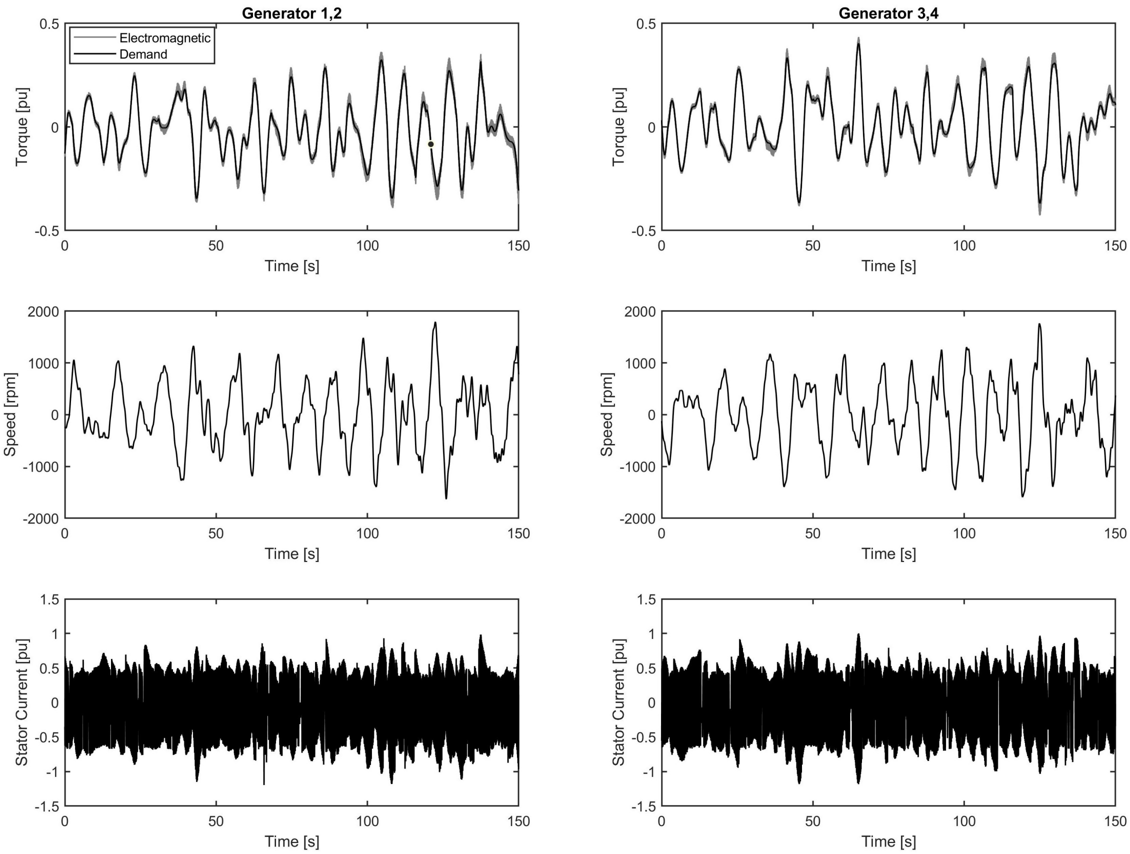

Fig. 8. Torque, rotational speed and stator current for PTO generators in irregular waves (Pierson-Moskowitz with $H_s = 3\text{m}$ $T_e = 10\text{s}$)

Figure 8 shows the torque, rotational speed and stator current for the PTO generators under the imposed irregular wave excitation. The sea-states were unidirectional and the WEC is aligned correctly meaning that the float orbit is planar in the surge and heave directions. This means that the four generators act as two pairs with identical motions and torques, hence results are presented for two generators only. The torque plots show that the PEC is able to control the electromagnetic torque of the generators to be very close to the demand. The generator speeds are seen to oscillate as expected with peak speeds within a sensible operating range. The stator currents are presented for the sake of completeness and display the expected behaviour and take reasonable values.

Figure 9 shows the real and reactive AC power measured at the grid, and the DC power measured at the supercapacitor and battery. The AC power is shown for two cases with and without short term energy storage on the DC bus. Positive real power and negative reactive power indicates power flow from the grid to the PTO. It can be seen that the supercapacitor in particular is able to inject the power required to avoid the need for this to happen. The battery is seen to respond much slower as expected due to the rate limitation. For the example simulations conducted here, which represent a commonly occurring medium intensity sea state, a supercapacitor of 1kJ capacity was used.

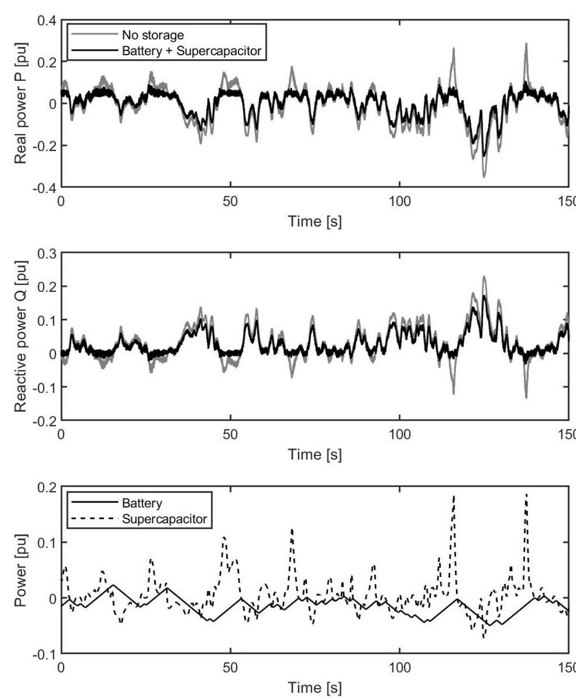

Fig. 9. Real and reactive power of PTO and supercapacitor/battery systems in irregular waves (Pierson-Moskowitz with $H_s = 3\text{m}$ $T_e = 10\text{s}$)

Figure 10 shows the DC bus voltage and SOC of the supercapacitor and battery. The DC bus voltage is seen to be well regulated to the required 750V by the active rectifier. The SOC of the supercapacitor and battery are seen to be maintained around a mean value throughout the transient, indicating that the charge management system is effective.

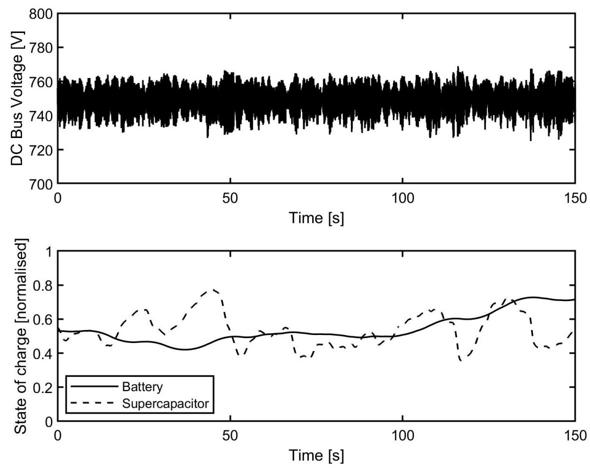

Fig. 10. DC Bus voltage and supercapacitor/battery system state-of-charge in irregular waves (Pierson-Moskowitz with $H_s = 3\text{m}$ $T_e = 10\text{s}$)

B. Power conversion in a lull

A lull of 30s duration was modelled together with an arbitrary requirement to supply the mean power achieved in the sea state of Figure 7, meaning the battery capacity was set at 10kJ. For comparison, this and the specified supercapacitor capacities are not dissimilar to those used in the study of an emergency power supply for a more electric aircraft in [13]. Figure 11 shows the torque, rotational speed and stator current for the PTO generators during a 30s lull in the wave conditions previously used. The lull is clearly seen on the torque and speed plots and again good torque control is observed.

Figure 12 shows the real and reactive power measured at the grid and the power flow to and from the supercapacitors and battery. The capacitor is seen to respond rapidly to the demanded power, with the battery providing sustained input power throughout the lull.

Figure 13 shows the DC bus voltage and SOC of the battery and capacitor. When the wave excitation resumes the battery continues to discharge, providing power to charge the supercapacitor according to the charge management scheme. Over the longer term the charge management will recharge the battery. This demonstrates the capability of the system to provide a supply of energy to the grid during a lull. The duration of lull that can be sustained depends on the power demand during that period and the capacity of the battery.

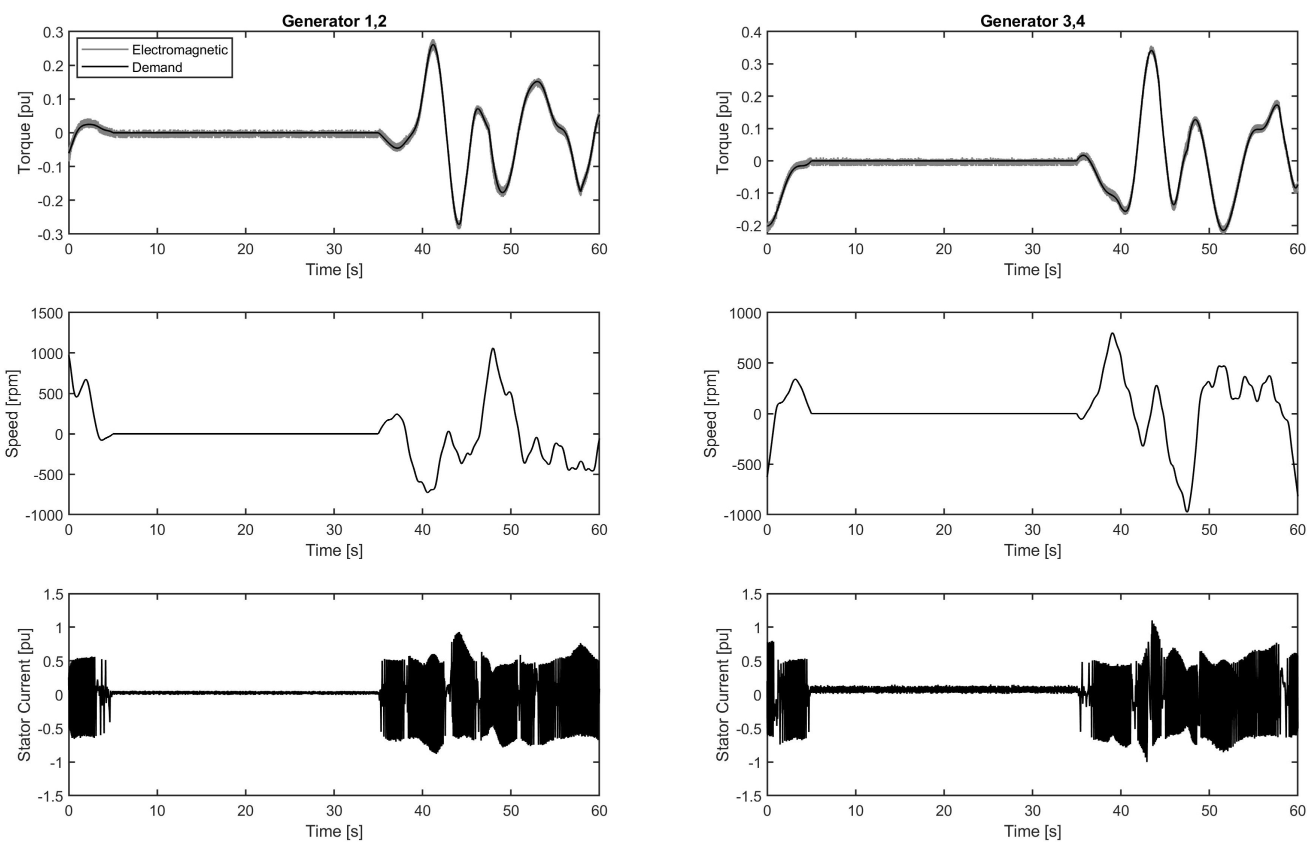

Fig. 11. Torque, rotational speed and stator current for PTO generators during a 30s lull in wave conditions

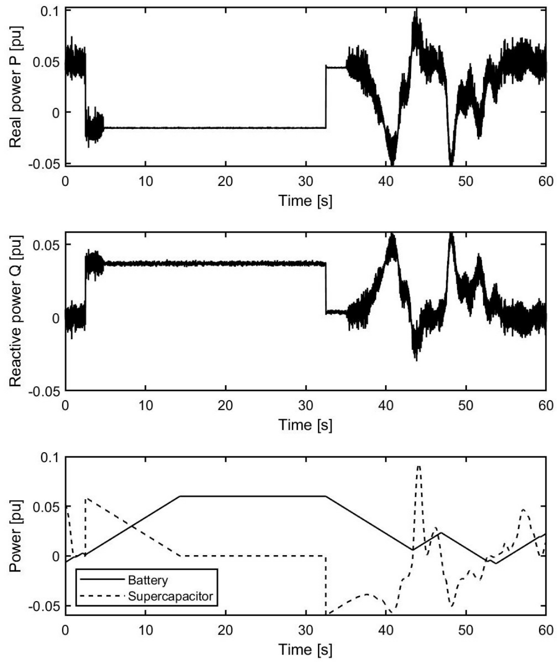

Fig. 12. Real and reactive power of PTO and supercapacitor/battery systems during a 30s lull in wave conditions

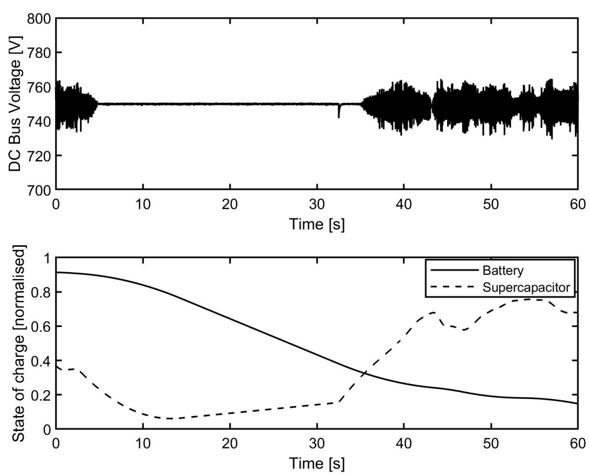

Fig. 13. DC Bus voltage and supercapacitor/battery system state-of-charge during a 30s lull in wave conditions

VI. Conclusions

A feasible PEC architecture to achieve a four quadrant torque demand from multiple generators has been simulated in irregular wave conditions and during a lull in wave excitation. The components of the PEC include four induction generators controlled by three phase inverters, a DC bus with short term energy storage provided by supercapacitors and batteries, and an active rectifier to control the DC bus voltage and provide AC power to the grid. The components are realistically modelled. It is shown that the torque and speed requirements of an active control strategy can be achieved and that the electrical energy storage can provide required reactive power on a wave-by-wave time scale and longer term energy supply during a lull in wave conditions. The WaveSub WEC has been used as a target device in order to make a meaningful study with realistic inputs. However the architecture of the PEC system is applicable to any device with a bi-directional rotary PTO requiring four-quadrant active control at the generators. Furthermore the architecture is readily expandable to arrays of devices. Appropriate spatial organisation of the devices could provide power smoothing and could eliminate the requirement for short-term energy storage. These are matters for further investigation.

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